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On the influence of load variations on lifetime and strength of wood

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Abstract

To days recommendations for probability and reliability analysis of wood structures do not fully recognize the influence of wood microstructure and creep on the mechanical behavior of wood. As a consequence, certain important features in wood design cannot be considered properly. Ignoring the basic materials behavior of wood cannot be 'covered or replaced' by purely mathematical handling of problems without loss of credibility.

Some examples are considered in this note, which cannot be solved following present recommendations:

- The influence of load variations on lifetime.
- The influence of load history on recycle-strength (residual strength).

It is demonstrated in this paper, how the problems just mentioned can be solved from respecting wood as a damaged viscoelastic material, meaning that wood is a cracked (damaged) material with creep.

1. Introduction

Application of so-called k_{MOD} methods [e.g.1,2] on problems with respect to lifetime and residual strength has serious limits [3]. The concept of k_{MOD} factors[1)] being constants is based on theories, which are basically developed from constant load experiments. The k_{MOD} method is very non-reliable at higher load frequency variations. Application of the Palmgren-Miners rule [4,5] is also questionable. This rule does not properly consider load frequency when viscoelastic materials are considered [6].

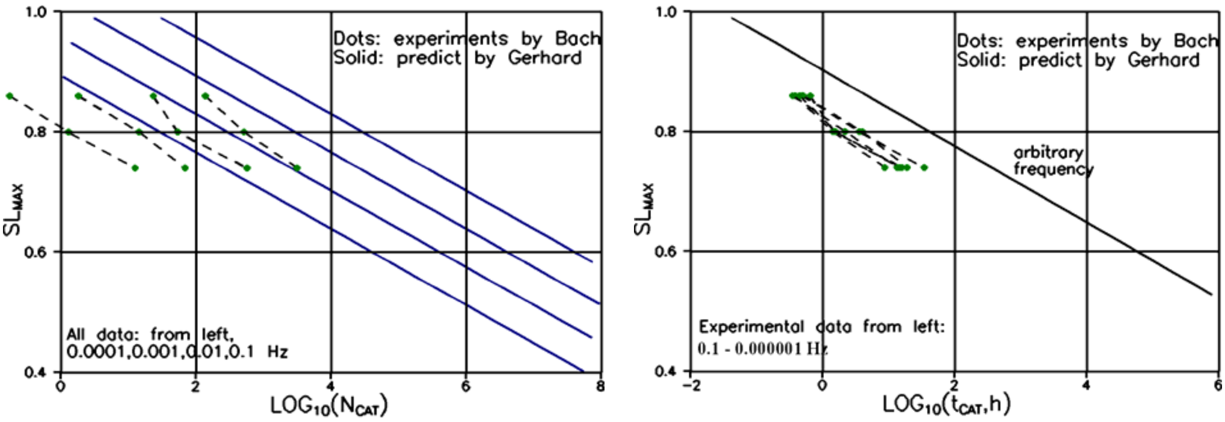

Figure 1. *Lifetime (load cycles and time) of clear wood subjected to a block load history as defined in figure 4 between 0 and a maximum of SL_{MAX} (load relative to wood strength). Overestimated lifetime is a consequence of not considering crack closure effects, see main text.*

The main reason, why present recommendations do not represent a sound basis for lifetime predictions of wood subjected to variable load is the fact that they do not consider energy dissipation appearing while changing from one load level to another (the phenomenon of crack closure). Recently, the quantitative consequences of disregarding this feature have been considered by the author in [7]. Overestimated lifetimes are typical consequences of such disregard.

An example of this feature is shown in Figure 1. The experimental lifetime data are the classical ones obtained by Bach [8] in tests exploring the influence of load level and frequency on time and load cycles to failure of wood subjected to varying load histories. The wood considered by Bach was clear

1) Widely spread concept of estimating long-term strength by multiplying short time strength with a codified factor, the so-called k_{MOD} factor.

wood specimens loaded in compression parallel to grain with a harmonic block load (see figure 4) shifting between 0 and a max load level of SL_{MAX} (load relative to strength).

The predictions presented in Figure 1 are reproduced from [7] where they are made by methods normally used in this context (Gerhard [9] and Barrett/Foschi [10,11]).

2. Viscoelastic lifetime prediction

It is demonstrated in this section, how lifetime predictions of wood can be improved significantly by considering wood as a damaged viscoelastic material – and furthermore get information of high importance with respect to residual (re-cycle) strength. As an extra advantage, solutions can be presented in a non-dimensional form such that they apply in general for a number of quality (FL) and viscoelastic (moisture) situations.

Basics

The basics of the authors DVM-theory (Damage Viscoelastic Material) presented in [12] and further developed in [e.g. 6,13,14] are the following:

- Damage in wood can be modeled by the Dugdale crack shown in Figure 2. The strength level (quality) of the wood considered is $FL = \sigma_{CR}/\sigma_L$ to be estimated from Figure 3. Traditional strength is σ_{CR}. Theoretical strength (no damage) is σ_L.
- The viscoelastic properties can be modeled by the Power-Law creep expression presented in Equation 1.

$$\begin{aligned}&\textit{Creep function}: \; C(t) = 1 + \left(\frac{t}{\tau}\right)^b \quad \textit{with creep power } b \approx 0.2 - 0.3 \\ &\textit{and relaxation time } \; \tau = \tau_{15} * 10^{(15-u)/10} \quad \textit{where } u(\%) \textit{ is moisture content and} \\ &\tau_{15} \approx 10 \textit{ days is relaxation time at } u = 15\% \textit{ for creep in damaged areas} \\ &\textit{(somewhat dependent of wood considered)}\end{aligned} \tag{1}$$

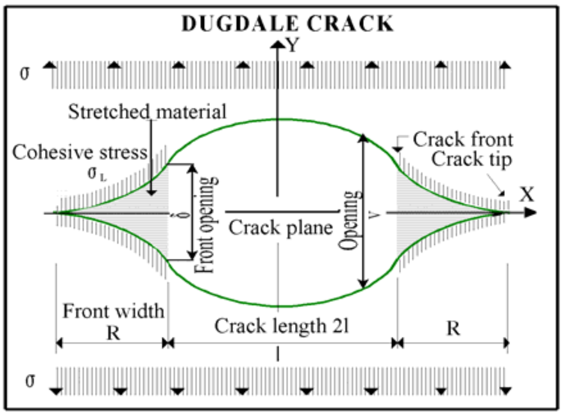

Figure 2. *Damage model for wood. Damage ratio, $\kappa = l/l_o$, subsequently used is length of expanding crack l relative to initial crack length.*

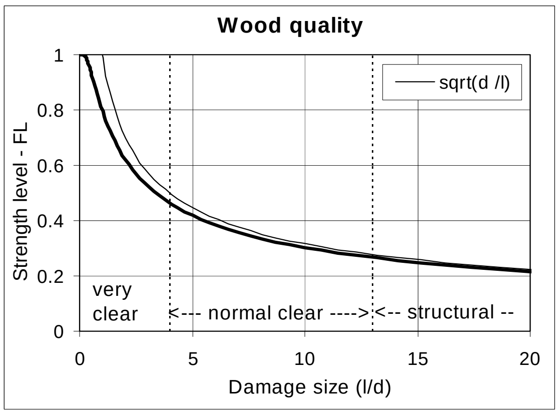

Figure 3. *Wood quality estimated from damage size, l, relative to the damage nucleus d = 0.3 mm. Strength levels of FL > 0.8 can only be obtained improving the microstructure of wood by decreasing the size of the damage nucleus.*

Lifetime prediction

The subsequent demonstration of DVM-predictions of wood lifetime is made by graphical presentations of results previously obtained by the author in [6,3] – and also presented in various working papers in the COST-E24 research project on 'Reliability of Analysis of Timber Structures' [15]. Specific versions of the theory have to be studied in publications referred to. Symbols used are summarized in the 'List of Symbols' at the end of this paper. Of special significance are the strength level FL previously defined – and the so-called fatigue parameters, (C,M) = (3,9) introduced in [6]. Load level SL =

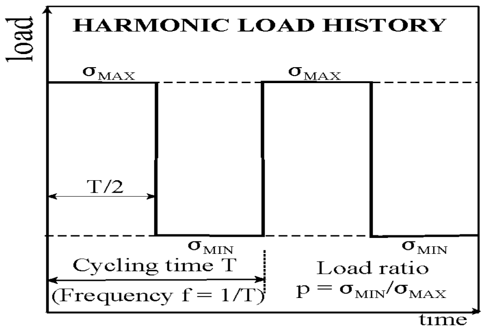

Figure 4. *Harmonic block load.*

σ/σ_{CR} is load relative to strength. The standard variable load history considered is the harmonic block load defined in Figure 4

An example of lifetime prediction is demonstrated in Figures 5 and 6. The experimental lifetime data are from Bach's work previously mentioned [8]. Predictions are made with creep and strength parameters (b,τ,FL) = (0.25, 1day,0.4) and fatigue parameters (C,M) = (3,9). The two figures have to be compared with Figures 1 and 2.

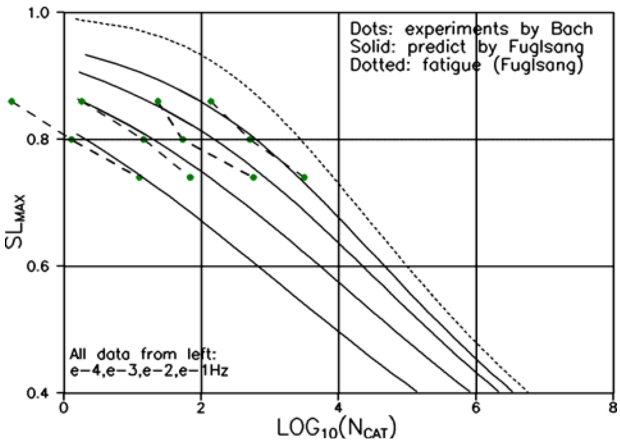

Figure 5. *Number of cycles to failure predicted by [6] with crack closure effects considered.*

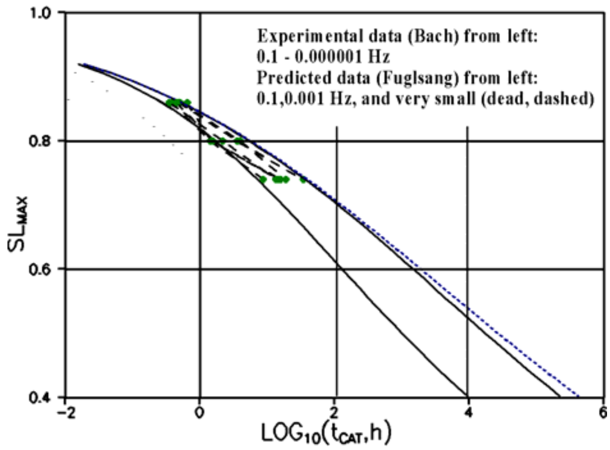

Figure 6. *Time to failure predicted by [6] with crack closure effects considered.*

3. Master graphs

As previously indicated, lifetime predictions can be made by general non-dimensional master graphs. Such are developed in [6] for any load, wood quality, FL (strength level), and creep relaxation time. The graphs shown in Figure 7 and 8 apply for a creep power of b = 0.25 and a load ratio of p = 0. As before, fatigue parameters are (C,M) = (3,9). Associated master graphs for re-cycle strength are shown in Figures 9 and 10.

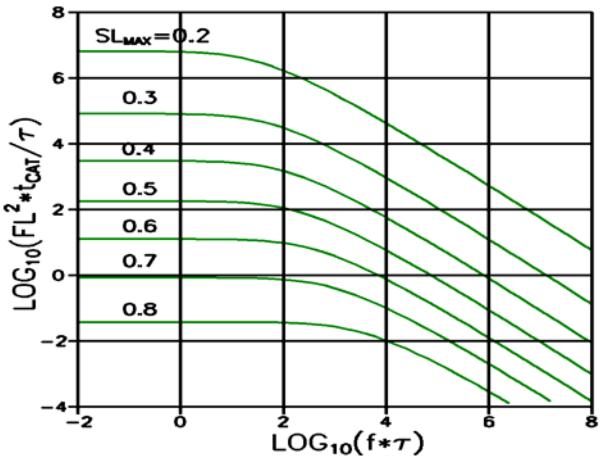

Figure 7. *Master graph. Time to failure. Load variation SL = 0 - SL_{MAX}.*

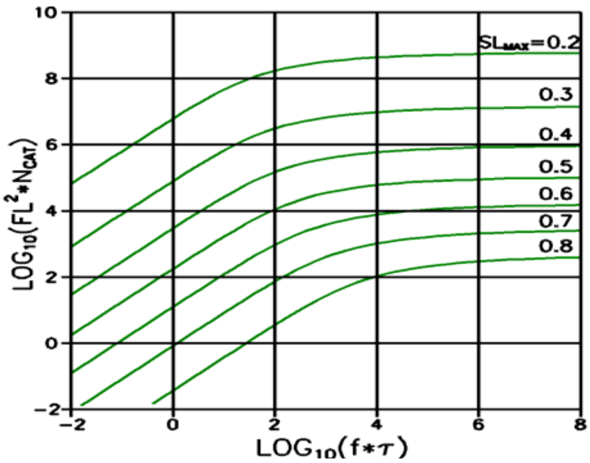

Figure 8. *Master graph. Number of cycles to failure. Load variation SL = 0 - SL_{MAX}.*

4. Design graphs

For practice the master graphs can be simplified [6] by combining the following constant load viscoelastic solutions and elastic fatigue solutions with a linear interpolation of these between the normalized frequencies f*τ = 10 and 10^5 when load ratio p < 0.5. (For p > 0.5. see [16]).

Dead load lifetime

$$\frac{d\kappa}{dt} = \frac{(\pi FL)^2}{8q\tau}\frac{\kappa SL^2}{[(\kappa SL^2)^{-1}-1]^{1/b}} \quad \textit{with} \quad q=\left[\frac{(1+b)(2+b)}{2}\right]^{1/b} \quad \textit{(damage rate)} \Rightarrow \tag{2}$$

$$\frac{t_{CAT}}{\tau} = \frac{8q}{\pi^2 FL^2 SL^2}\int_0^{1/SL^2-1}\frac{x^{1/b}}{1+x}dx \qquad (N_{CAT}=t_{CAT}/T = f*t_{CAT})$$

Dynamic (Elastic fatigue)

$$NCAT = \frac{1}{G\,SL_{MAX}^2}\left[\frac{1-SL_{MAX}^{M-2}}{(M-2)SL_{MAX}^{M-2}} - \frac{1-SL_{MAX}^{M-4}}{(M-4)SL_{MAX}^{M-4}}\right] \quad \textit{with}\ G = \frac{CFL^2}{13}\left[\frac{1-p^2}{2}\right]^M \tag{3}$$

$(t_{CAT}=N_{CAT}*T=N_{CAT}/f)$ *fatigue parameters* $(C,M)=(3,9)$

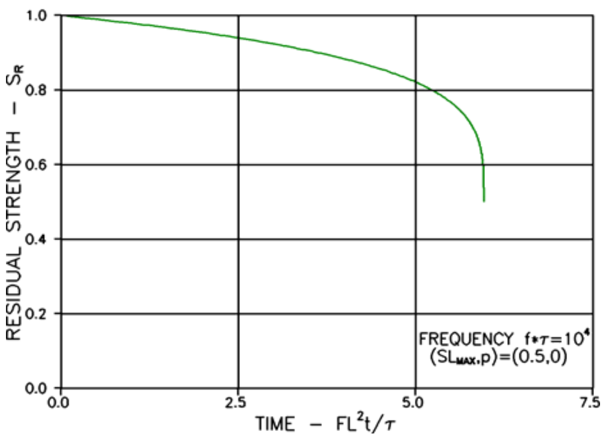

Figure 9. *Master graph. Re-cycle strength as a function of time under variable load. Load variation SL = 0 – 0.5. Load frequency.* $f\tau = 10^4$.

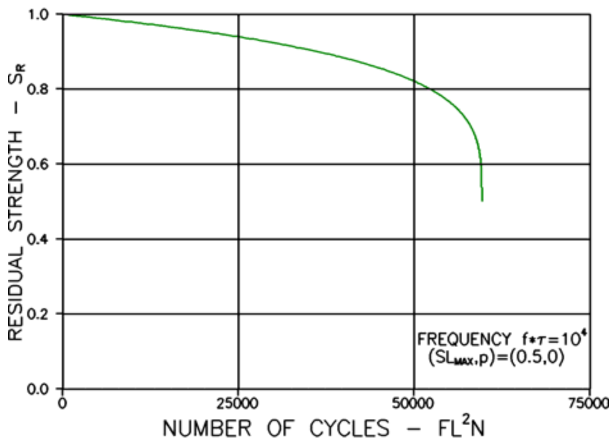

Figure 10. *Master graph. Re-cycle strength as a function of number of load cycles. Load variation SL = 0 – 0.5. Load frequency,* $f\tau = 10^4$.

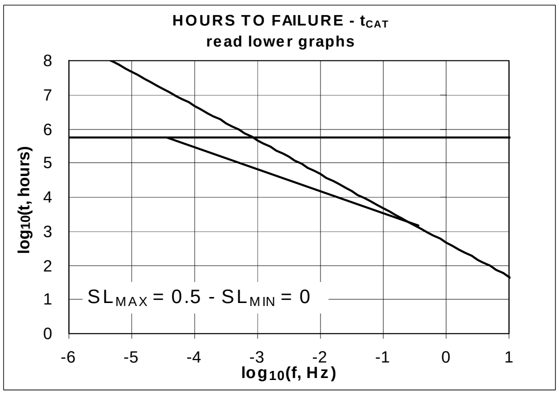

Figure 11. *Design graph. Easy estimate of time to failure. Example:* $SL_{MAX} = 0.5$, $p = 0$, $FL = 0.25$, $b = 0.20$, *and* $\tau = 3.2$ *days* ($u = 20\%$).

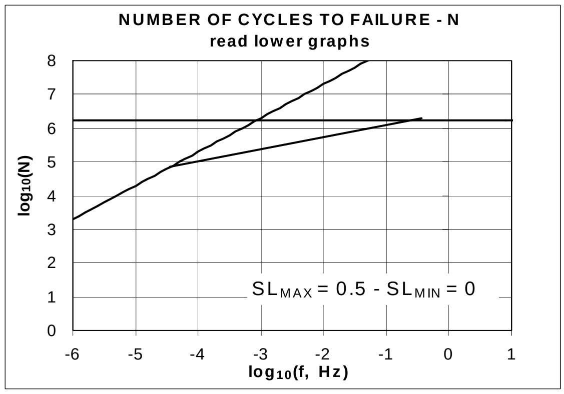

Figure 12. *Design graph. Easy estimate of number of load cycles to failure. Example:* $SL_{MAX} = 0.5$, $p = 0$, $FL = 0.25$, $b = 0.20$, *and* $\tau = 3.2$ *days* ($u = 20\%$)

5. Final remarks

Harmonic load variations have been assumed in this note. An important future research project is to develop a lifetime theory, which applies for more general variations (non-harmonic load histories such as sudden peak loads). It has been demonstrated in [17] that the DVM theory in [6] has the basic potentials to be further generalized for such loads. Figures 13 to 16, reproduced from [3,18], demonstrate some results obtained by a pilot theory being tested to predict residual strength of wood subjected to load histories caused by earthquakes.

With respect to the potentials of the DVM-theory should also be mentioned that research are presently being made [14] to generalize the results of the theory also to apply at variable moisture conditions. It is suggested that the influence of moisture variations very often can be considered by modifying the creep properties of wood such that the Power-Law description in Equation 1 can be maintained without introducing complicated mechano-sorptive mechanisms. It is obvious that such approach will increase very much the practical applicability of the 'non-dimensional' master graphs presented in this article.

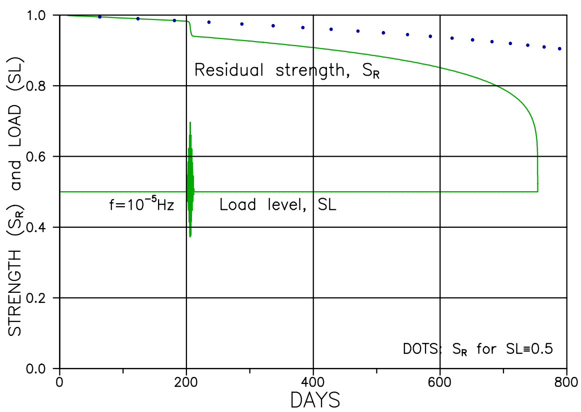

Figure 13. *Lifetime and residual strength of wood, (FL,b,τ) = (0.4,0.25,1 day), loaded with SL = 0.5 + 1.e-5 Hz Pulse load at t ≈ 206 days. The dots indicate residual strength if pulse load is absent.*

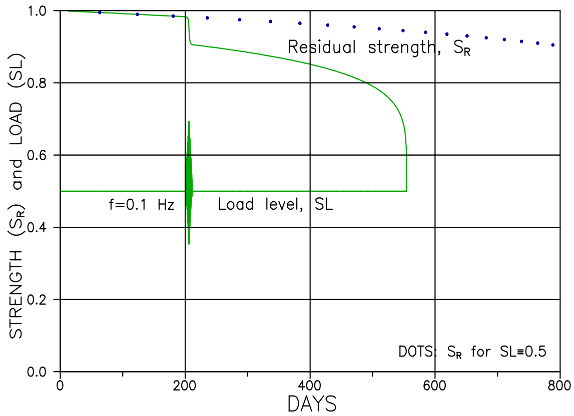

Figure 14. *Lifetime and residual strength of wood, (FL,b,τ) = (0.4,0.25,1 day), loaded with SL = 0.5 + 0.1 Hz Pulse load at t ≈ 206 days. The dots indicate residual strength if pulse load is absent.*

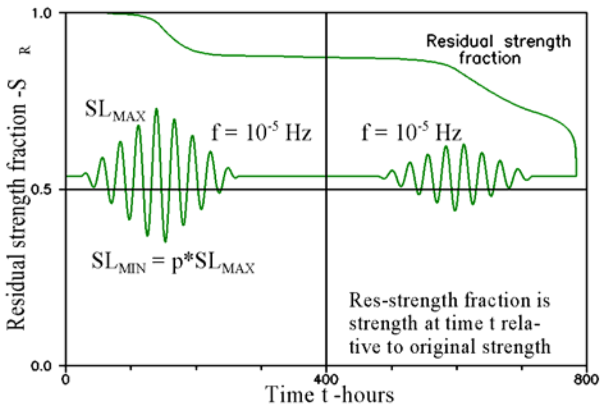

Figure 15. *Residual strength and lifetime of wood subjected to load as indicated with (FL,b, τ) = (0.4, 0.25. 1 dav).*

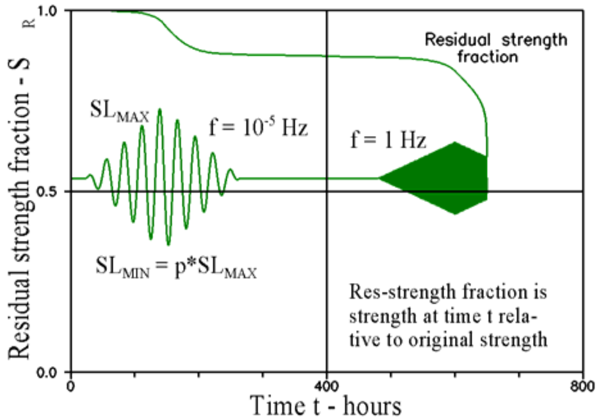

Figure 16. *Residual strength and lifetime of wood subjected to load as indicated with (FL,b, τ) = (0.4, 0.25, 1 day).*

Notations

Load and strength	
Load level	$SL = \sigma/\sigma_{CR}$
Strength level (wood quality)	$FL = \sigma_{CR}/\sigma_L$
Residual strength	$S_R = \sigma_{CR}(t)/\sigma_{CR}$
Load	σ
Max load	σ_{MAX}
Min load	σ_{MIN}
Load ratio	$p = \sigma_{MIN}/\sigma_{MAX}$
Cyclic time	T
Frequency	f = 1/T
Real strength at t = 0	σ_{CR}
Real strength at t	$\sigma_{CR}(t)$
Theoretical strength (no damage)	σ_L
Damage	
Damage ratio (or just damage)	$\kappa = l/l_o$
Immediate crack length	l
Initial crack length	l_o
Fatigue parameters in DVM model	(C, M) = (3,9)

Time and creep

Time in general	t
Relaxation time in creep	τ
Creep power	b
Time shift parameter	$q = (0.5(1 + b)(2 + b))^{1/b}$
Normalized creep function	$C = 1 + (t/\tau)^b$

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